Two-Pump Distributed Parametric Amplification for Optically Powered Communication System

Xing Xu, Chi Zhang, T. I. Yuk and Kenneth K. Y. Wong*

Photonics System Research Lab, Department of Electrical and Electronic Engineering,
The University of Hong Kong, Hong Kong S.A.R., China.
**Email: kywong@eee.hku.hk*

Abstract: We demonstrate a power-efficient two-pump distributed parametric amplification (DPA) system. The residual pumps are recycled to power up the receiving component. At the BER of 10^{-9}, power penalties less than 2.3-dB are measured with 10-dB gain.

OCIS codes: (060.2320) Fiber optics amplifiers and oscillators; (190.4410) Nonlinear optics, parametric processes

1. Introduction

Distributed parametric amplification (DPA), one of the distributed amplification candidates, has been studied recently [1,2]. Although once being regarded as detrimental [3,4], DPA has several advantages over distributed Raman amplification (DRA), including lower pump power, free from double Rayleigh scattering (DRS) and idler generation [1]. Instead of using the specially fabricated highly-nonlinear dispersion-shifted fiber (HNL-DSF) as the amplification medium [5–8], DPA adopts the conventional low-loss transmission fibers, while the signal transmission and amplification can be achieved simultaneously. The most favorable merit of DPA lies in its capability of minimizing signal power variation along the fiber, which provides the best tradeoff between the noise figure (NF) and fiber nonlinearities [9]. One-pump DPA has been investigated in [1,2,10]. However, inherited from one-pump optical parametric amplifier (OPA), the gain spectrum of one-pump DPA is not uniform, not to mention the discontinuity between two gain side bands, although its experimental setup is simpler. Two-pump DPA, alike two-pump OPA [6,7], can resolve the dilemma. Flattened gain spectrum [5], polarization-transparent operation [7], narrow-linewidth idler spectrum and effective suppression of stimulated Brillouin scattering (SBS) with complementary phase-dithering [8], these are all advantages of two-pump scheme. While in this paper, an power-efficient optically powered WDM communication system with two-pump DPA has been demonstrated. In order to enhance the energy-efficiency of the communication system, the residual parametric pump power after DPA can be recycled as the power supply for the receiving component. In the mean time, the energy-efficiency of the proposed scheme is guaranteed by a commercially available photovoltaic (PV) cell, with a typical power conversion ratio of 20% (@1300 nm to 1550 nm optical input).

2. Experimental Setup

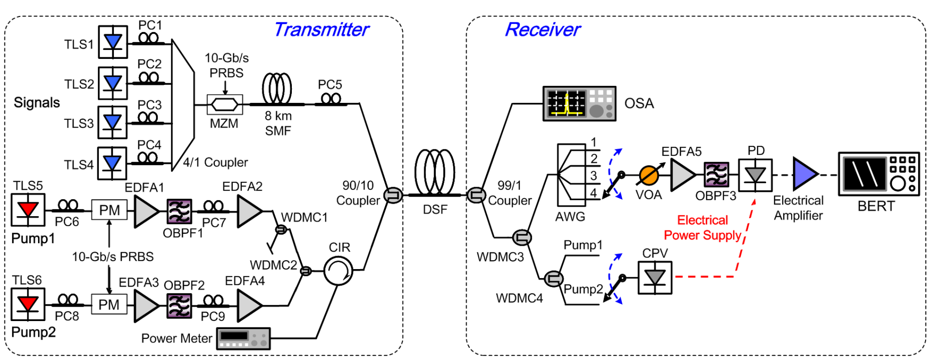

Fig. 1. Experimental setup for the power-efficient two-pump DPA. MZM: Mach-Zehnder modulator, WDMC: WDM coupler, AWG: arrayed-waveguide grating, CPV: concentrated photovoltaic cell, VOA: variable optical attenuator, PD: photodiode.

The experimental setup is shown in Fig. 1. The WDM signals, located at 1542.9, 1543.76, 1544.65 and 1545.45 nm, were generated from four continuous-wave (CW) tunable laser sources (TLS1-4) and intensity-modulated together by a Mach-Zehnder modulator (MZM) driven by 10 Gb/s 2^7-1 pseudorandom binary sequence (PRBS). A spool of 8 km single-mode fiber (SMF) was then deployed to de-correlate different WDM channels in the time domain. On the other hand, the pumps, wavelength at 1535.5 and 1561.3 nm, respectively (TLS5, TLS6), were first phase-dithered with two phase modulators (PM), driven by a 10 Gb/s 2^{23}-1 PRBS, to suppress the SBS. Two branches of double-stage erbium-doped fiber amplifiers (EDFA) then amplified the pump powers upto 21.3 (@1535.5 nm) and 19.8 dBm (@1561.3 nm). The optical band pass filters (OBPF1, OBPF2) were used to reduce the amplified spontaneous emission (ASE) noise level from EDFA1 and EDFA3. Due to the high power output of EDFA2 and EDFA4, WDM couplers (WDMC1 and WDMC2) were used for both pump combination and ASE noise diminution. A circulator (CIR) was inserted after WDMC2 to avoid the reflection and to monitor the SBS level. After combining with a 90/10 coupler, the pumps and the signals were launched together into a spool of 10 km DSF ($\gamma = 2\ W^{-1}km^{-1}$, λ_0 = 1548 nm). The signal powers at the input of DSF were maintained at less than -24 dBm, while the pump powers at the same point were 17.8 (@1535.5 nm) and 16.2 dBm (@1561.3 nm). Thus, after the parametric process, the pumps were not depleted and the generation of signal-related nonlinear effects, such as the four-wave-mixing (FWM) and cross-gain modulation (XGM), would be insignificant. The SOP of the pumps and the signals were aligned by polarization controllers (PC5, PC7 and PC9) to attain the maximum optical parametric gain. At the receiving end, after divided by WDM couplers (WDMC3, WDMC4), the residual pump powers of 13.05 and 11.69 dBm were sent separately (pump1 and 2 in Fig. 1) to the CPV cell. And its electrical output was used to power up the signal receiving component. Finally, 4-channel WDM signals were de-multiplexed by an arrayed-waveguide grating (AWG) and the performance of each channel (points 1-4 in Fig. 1) was then quantified by the bit-error rate tester (BERT).

3. Experimental Results and Discussion

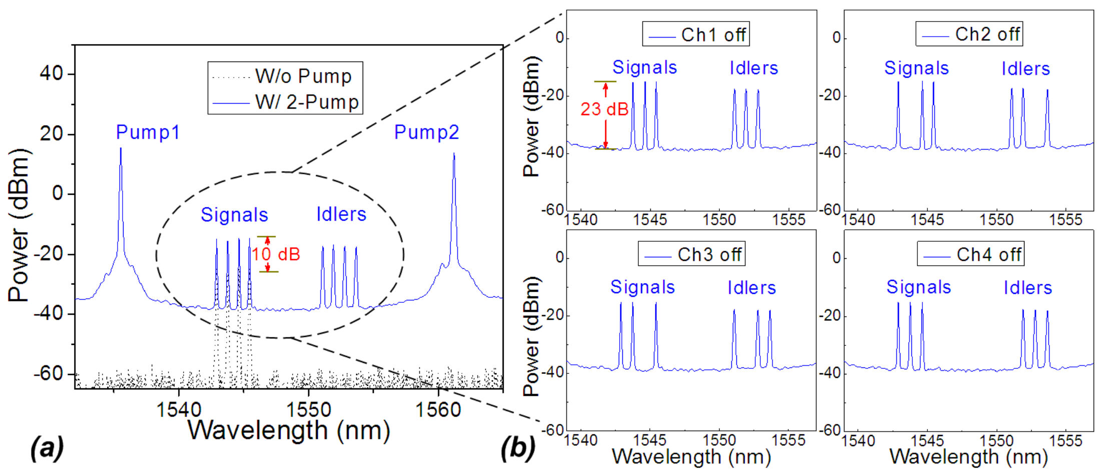

Fig. 2. Optical spectra at the output of DSF: (a) WDM signals spectrum with (blue solid line) and without (black dotted line) parametric pumps; (b) Enlarged WDM signal spectra after DPA with one channel off. (OSA resolution bandwidth: 0.06 nm)

The optical spectra at the output of DSF are shown in Fig. 2. The signal powers at the input of DSF were -24.94, -25.35, -24.73 and -24.81 dBm, respectively. The corresponding on-off parametric gains were 10.01, 10.07, 10.13 and 10.19-dB. During the experiment, each channel was switched off sequentially to quantify the signal crosstalk (Fig. 2(b)) through the optical spectrum analyzer (OSA). It can be observed that there was no observable spurious FWM component (more than 23-dB lower than the signals) generated. The insets of Fig. 3(a) illustrate the eye diagrams of the received WDM signals. Clear and widely open eye diagrams were recorded, which indicate the high quality of the receiving WDM signals. The noise on the mark level was mainly due to the conversion of pump phase modulation to signal intensity modulation (PM-IM conversion) during the parametric process along the DSF. The corresponding BER results of each channel was shown in Fig. 3(a). Error-free operations were attained for all channels and the power penalties incurred range from 1.9 to 2.3-dB at the BER of 10^{-9}.

In our experiment, a InP-based concentrated photovoltaic (CPV) cell, with a typical power conversion ratio η_c of

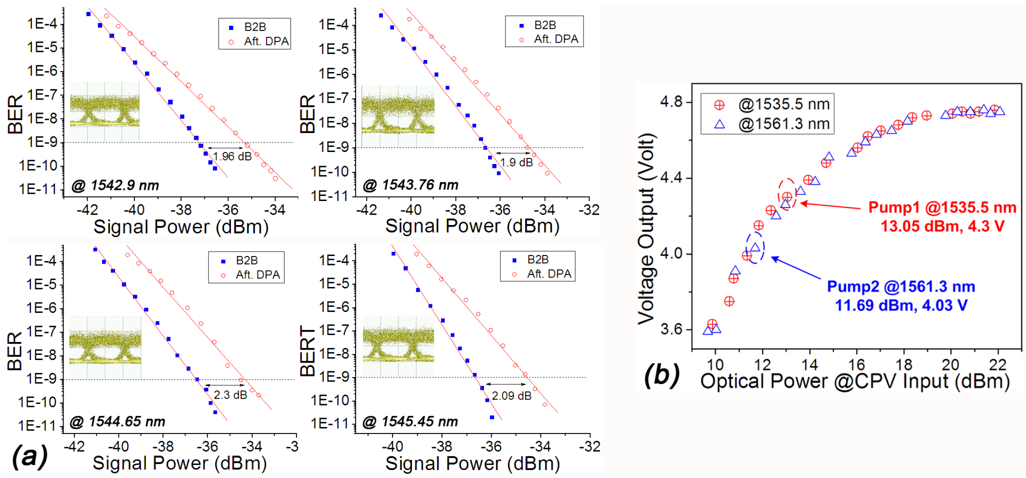

Fig. 3. (a) BER plots for the back-to-back and the signals after DPA with the inset of signal eye-diagrams; (b) The response curve of the CPV cell with the input optical pump light at 1535.5 nm (red circle with cross) and 1561.3 nm (blue triangle).

20% (maximum up to 26%), was used. Fig. 3(b) shows the output curves of the CPV cell with input optical pump at different wavelengths and powers. According to the curve, the corresponding outputs could reach 4.3 V for 1535.5 nm pump and 4.03 V for 1561.3 nm pump, which were enough for the bias voltage of the 5-V photodiode (PD, in Fig. 1) used at the receiving end as the optical-to-electrical converter in our experiment. Different from our former one-pump DPA experiment [2, 10], two residual parametric pumps after DPA process can be used individually as the power supply. Thus, with additional devices (e.g. another CPV cell) at the receiver, both pumps could be recycled simultaneously to power up different components.

4. Conclusion

We have demonstrated a power-efficient two-pump DPA system. Clear and widely open eye diagrams have been obtained for all WDM channels after the parametric process, with a less than or equal to 2.3-dB power penalty at 10^{-9} BER. By utilizing the remaining optical parametric pumps as the power supply for the receiving end, the energy-efficiency of the whole system has been promoted.

Acknowledgment

The work described in this paper was partially supported by the grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Projects No. HKU 7179/08E and HKU 7183/09E).

References

1. G. Kalogerakis et al., “Transmission of optical communication signals by distributed parametric amplification,” J. Lightwave Technol., **23**, 2945-2953, 2005.
2. X. Xu et al., “Optically powered WDM signal transmission system with distributed parametric amplification,” IEEE Photon. Tech. Lett., **22**, 1232-1234, 2010.
3. N. Henmi et al., ”A new design arrangement of transmission fiber dispersion for suppressing nonlinear degradation in long-distance optical transmission systems with optical repeater amplifiers,” J. Lightwave Technol., **11**, 1615-1621, 1993.
4. P. Serena et al., ”Parametric-Gain Approach to the Analysis of Single-Channel DPSK/DQPSK Systems With Nonlinear Phase Noise,” J. Lightwave Technol., **24**, 2026-2037, 2006.
5. M. E. Marhic et al., “Broadband fiber optical parametric amplifiers,” Opt. Lett., **21**, 573-575, 1996.
6. C. S. Bres et al., “Self-seeded multicasting of 320 Gb/s data in a 2-pump parametric amplifier,” Proceedings of OFC 2009. OMH7.
7. K. K. Y. Wong et al., “Polarization-independent two-pump fiber optical parametric amplifier,” IEEE Photon. Tech. Lett., **14**, 911-913, 2002.
8. K. K. Y. Wong et al., “Phase-conjugate pump dithering for high-quality idler generation in a fiber optical parametric amplifier,” IEEE Photon. Tech. Lett., **15**, 33-35, 2003.
9. C. McKinstrie et al., “Quantum noise properties of parametric processes,” Opt. Express, **13**, 4986-5012, 2005.
10. X. Xu et al., “Optically powered communication system with distributed amplifiers,” J. Lightwave Technol., **27**, available online, 2010.